Construction and Building Materials 190 (2018) 24–37

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Optimization of hybrid fibres in engineered cementitious composites

Bashar S. Mohammed *, Veerendrakumar C. Khed *, Mohd Shahir Liew

Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak Darul Ridzuan, Malaysia

HIGHLIGHTS

- Optimization of hybrid fibres leads to the improve the performance of HFRECC.
- 0.5% tirewire and 1.5% of PVA hybrid fibre found to be optimum ratio.
- RSM models have been developed to predict the strengths of HFRECC.

ARTICLE INFO

Article history:
Received 11 April 2018
Received in revised form 23 August 2018
Accepted 28 August 2018

Keywords:
Hybrid fibres
Tirewire
PVA
Self-compacting
Optimization
RSM

ABSTRACT

New hybrid fibre reinforced cementitious composite developed using waste materials in the form of tirewires in combination with the PVA (Polyvinyl alcohol) fibers. The two kinds of fibres have been incorporated in the RSM (Response surface methodology) technique from the Design-expert software to evaluate the hybrid proportion of fibers. The Hybrid fibres in ECC (Engineered cementitious composite), with appropriate quantity of high and low modulus fibers is anticipated to enhance both the tensile strength (modulus of elasticity, bulk strength) and strain capacity (mainly for energy absorption). The fresh properties for self-compacting were satisfied according to EFNARC guidelines and observed that tirewire fibre diminished the workability and was preserved through the addition of PVA and superplasticizer. The hardened properties such as flexural strength, direct tensile strength, modulus of elasticity and shrinkage strain were optimized by developing the model equations through ANOVA (analysis of variance) validation with the more than 95% of significance. The appropriate proportions as 0.5% of tirewire and 1.5% of PVA fibers were obtained. The results revealed that the hybrid proportion of fibres adversely effected on workability and it produced a favourable influence on flexural strength, tensile strength and modulus of elasticity. The PVA fibres helped in increasing the strain hardening portion for the hybrid fibre reinforced engineered cementitious composite (HFRECC) and was able to maintain strain capacity up to 5%. The optimized results were validated experimentally with high desirability value of more than 0.97 and the variation between experimental and optimized results from RSM was found to be less than 5%.

1. Introduction

ECC is one of the fibre reinforced high performance composite based on the micro and fracture mechanics theory which deals with high toughness, pseudo-strain hardening with the multiple cracks [1]. The structural samples prepared by ECC material reduced self-weight of the structure [2]. Generally, ECC comprises of cement, fly ash, sand, fibres and chemical admixtures. Different volume fractions in the mix with the specific characterization of fibre performs in tailoring the constituent material properties of the composites [3]. ECC has tensile strain capacity in the range of 3–7% against 0.01% of conventional concrete, a tensile strength of 4–6 MPa, compressive strength is around 30–80 MPa and 0.4–0.65% of compressive strain capacity [4]. ECC has the capacity to control failure mode for average crack width up to 60 μm [5]. ECC was developed by V.C Li and he stated that " ECC is tremendously damage control material which remains ductile in extreme shear loading circumstances"[6]. Several kinds of ECC are self-compacting [7], lightweight [8], extruded [9] and shotcrete ECC [10].

In previous studies, fibres like PVA, polyethylene (PE) and polypropylene (PP) have been utilized to develop the various properties in ECCs. Many researchers used the PVA fibres due to its better hydrophilic nature which makes it to develop the strong chemical bond with cementitious matrix [11]. In comparison with the PE fibres, PVA is cheaper and has better tensile strength than the PP fibres. Therefore, PVA has been widely used in ECC. For 2%

* Corresponding authors.
E-mail address: bashar.mohammed@utp.edu.my (B.S. Mohammed).

https://doi.org/10.1016/j.conbuildmat.2018.08.188
0950-0618/

of fibre volume in PVA-ECC, up to 4% of tensile strain capacity and 4.5 MPa of ultimate strength can be achieved [12].

In the past, researchers had studied on mechanical properties of ECC using various fibres such as PVA (E ≃ 40 GPa, tensile strength ≃ 1600 MPa), polyethylene (E ≃ 66 GPa, tensile strength ≃ 2700 MPa), steel fibres (E ≃ 200 GPa, tensile strength ≃ 2700 MPa). These fibres have the large difference in their modulus of elasticity, tensile strength. Thus, low modulus fibre contributes to high energy absorption, increase in the ductility and the steel fibres are good in producing higher modulus of elasticity in ECC [13]. The fibres play role in controlling the growth of cracks, thus the growth of micro cracks is restrained by microfibers and the development of larger cracks are inhibited by large fibres. Therefore, it is believed that the hybrid fibres containing more than one type and size of fibre could form synergistic effects to get better performance. Hybridization of low and high modulus fibres in cementitious composite was resulted in improved strain capacity [14].

The steel-PVA hybrid fibre reinforced ECC tested on the composite panel which revealed a better impact resisting capacity, enhanced fibre bridging capability and improved durability properties [15]. The hybrid fibre combination of PVA and SMA (shape memory alloy) in ECC increased the tensile and flexural strength by 59% and 97% respectively, whereas workability decreased up to 43% with the increased quantity of SMA fibres [16]. The ECC with PVA and steel fibre of different sizes helped in arresting the micro and macro cracks along with the improved dynamic behaviour [13]. The bagasse and steel fibres were used as hybrid fibres in ECC, which reduced the mechanical behaviour in terms of modulus of rupture and Young's modulus due to induction of high porosity by the fibres [17]. With an optimum percentage of steel and PVA fibres in nano-silica modified ECC, it could achieve the outstanding mechanical properties and control over the micro-cracks and it was noticed that fly ash performed like water reducing agent [18]. The hybrid fibre combination mainly steel and polypropylene in cementitious composite contributed to the improvement of seismic behaviour in terms of increased energy dissipation capacity along with the stiffness and load carrying capacity [19]. Proper proportions of oiled and unoiled PVA fibres in ECC resulted in maximum bridging stress with strain hardening and steady-state cracking [1]. CFRP-ECC hybrid fibre brings about 2.8% of tensile strain and could get higher flexural strength [20]. The CFRP-ECC hybrid fibre could sustain the elevated temperature and the composite matrix was sensitive to the temperature [21]. Under high temperature, the hybrid fibre (PVA and steel fibre) cementitious composite behaviour was brittle and was less vulnerable for less than 100 °C [22].

In the past, many studies have been performed for various kind of recycled fibres such as glass fibre, nylon fibre, polypropylene fibres, carbon fibres, steel fibres and a hybrid combination of the fibres in concrete. Also, the recycled fibres in the form of tirewire, which is extracted from the waste tyres were used in the concrete as a replacement for the industrially manufactured steel fibres. These fibres improved the properties of the fibre reinforced concrete (FRC) in terms of shear and toughness behaviour [23]. The tirewires were more influential in controlling the development of microcracks in comparison to the conventional fibres in the FRC and also the hybrid mixture of fibres offered the synergetic effect [24]. Recycled fibres enhanced the first crack strength and ultimate load capacity along with the toughness and flexural stiffness for self-compacting FRC [25]. Tirewire fibre benefits in reducing the brittle behaviour of cementitious composites by improving its post cracking resistance and toughness, thus it acts as a sustainable material for the construction industry [26].

Several researchers have incorporated the statistical method for experimental design and optimization in concrete technology, chemical engineering etc. The RSM was used to study the mechanical and durability properties for different contents of recycled fine and coarse aggregate [27]. The central composite design method (CCD) of RSM was employed to improve the thermal transmittance in the light weight concrete hollow bricks [28]. RSM was used in designing the mix proportion for ultra-high performance of fibre reinforced concrete and optimized for flow, compressive, bending and direct tensile strengths [29]. The freezing and fatigue actions for recycled pavement were assessed using the RSM and it was concluded that RSM model fits well [30]. The statistical method delivered the design mix support for concrete made with wood chipping as a partial replacement with fine aggregate [31]. The optimum solution in the form of maximizing the compressive strength and concurrently economizing the fibrous concrete mixtures was performed using RSM technique [32]. RSM was incorporated to design the mix proportion for concrete containing the paper mill residuals and it was found that RSM is useful in obtaining the appropriate estimation of the compressive strength and slump flow [33].

In this study, the hybrid proportion of PVA and tirewire as steel fibres were optimised in ECC using statistical technique RSM for hardened properties such as compression strength, flexural strength, tensile strength, modulus of elasticity and shrinkage.

2. Experimental program

2.1. Materials and properties

The constituent materials used for self-compacting hybrid fibre reinforced ECC are ordinary Portland cement (OPC) Type-1 according to the requirements of ASTM C150. Class F fly ash (FA) which conform to the requirements of ASTM C618 with quantity of ($Al_2O_3 + Fe_2O_3 + SiO_2$) about 82.12% and below 6% loss on ignition. Fly ash is utilized in ECC in order to reduce the material cost and also it acts as an excellent water reducing material when used in high volume to give the boost for fresh properties of self-compacting. Fly ash is waste material and is a by-product of pulverized coal being burned in an electrical generating station and it is classified as cement replacement materials which have pozzolanic properties. Using Fly ash in ECC mixtures results in multiple advantages such as increase strength, reduce permeability (improve durability), reduce hydration heat (less thermal cracking), reduce efflorescence. Cleanly washed river sand as fine aggregate which has an average grain size of 450 μm, potable tap water, two types of fibres were included in percentages by volume which are Tirewire fibre and PVA fibres shown in Fig. 1(a) and (b) respectively. PVA fibres are monofilament fibre and the tirewire fibre are steel wires which are extracted from waste tyres by magnetic separation process. Since this mixture is self-compacting which has free-flowing ability on its own under gravity into the formwork and surrounding the steel reinforcement. Self-compacting helps to increase the construction speed, quality of structural member which results in high durability and smooth surface finishing [34]. Therefore, a high range water reducing (HRWR) agent "Sika Viscocrete" was used, which is a commercially available polycarboxylate based superplasticizer in aqueous solution form with pH value of 6.2, specific gravity of 1.08 and chloride ion content is zero percent. The oxide content of OPC and FA are prescribed in Table 1 and properties of PVA and tirewire fibres are depicted in Table 2.

2.2. Mix proportions

Mix proportions have been developed using the central composite (CCD) of RSM in Design-Expert software version 10. The hybrid fibre combination in the form of tirewire and PVA fibres were incorporated in the design to develop the mix proportions. Thirteen mixtures of HFRECC were prepared as shown in Table 3. The variables PVA and tirewire were employed in the range of zero to 2% and zero to 0.6% respectively. PVA fibre range was selected based on the previous studies [2] and the tirewire fibres range were selected on the basis preliminary experimental observations made in terms fibre balling which led to the non-uniform dispersion of fibres. These mixtures were organised in accordance with the regulations of EFNARC 2002 [35], which was executed by balancing the superplastisizer (HRWR) for the required flowability. The HRWR was mixed in water by total weight percentage of cement and Fly ash. The high percentage of tirewire fibre demanded the higher percentage of HRWR in accordance with the requirement of self-compacting. However, the adverse effects of HRWR overdose in the form of bleeding and segregation were noticed during test fresh properties.